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Latitudinal Variations in Jovian Stratospheric Temperature

R. D. CESS, BARBARA E. CARLSON, AND JOHN CALDWELL[1]

Laboratory for Planetary Atmospheres Research, State University of New York, Stony Brook, New York 11794

I. G. NOLT[1]

Atmospheric Physics and Chemistry Laboratory, NOAA, Boulder, Colorado 80302

F. C. GILLETT

Kitt Peak National Observatory, Tucson, Arizona 85726

AND

A. T. TOKUNAGA[1,2]

Steward Observatory, University of Arizona, Tucson, Arizona 85726

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Ground-based observations of Jupiter show that the planet's stratospheric and tropospheric thermal emission are anticorrelated. The observations can possibly be explained by latitudinal variations in cloud altitude. These variations cause differential stratospheric heating by sunlight which is reflected off the clouds and then absorbed within the stratosphere by visible and near-infrared bands of methane.

INTRODUCTION

Caldwell *et al.* (1979) have recently presented evidence for seasonal temperature variations within the stratosphere of Jupiter, in the form of north–south drift scans through the central meridian at infrared wavelengths of 7.9, 17.8, 19.7 μm, with the respective bandwidths being 0.12, 0.6, and 1.7 μm. These data were obtained using the 4-m telescope at KPNO on 8 March, 1979. Radiation at 7.9 μm, in the wing of the strong methane (CH_4) fundamental ν_4 band, originates near the 10-mbar pressure level within the Jovian stratosphere, whereas the longer wavelength radiation comes from below the 100-mbar level within the troposphere (Orton, 1977).

Caldwell *et al.* (1979) demonstrated that an observed north–south asymmetry in 7.9-μm emission is consistent with a seasonal stratospheric temperature variation, including phase lag, driven mainly through absorption of solar radiation by an atmospheric aerosol layer. Limb brightening, particularly at the North Pole, is due to the stratospheric temperature inversion. The observed north–south asymmetry in stratospheric temperature is, moreover, in excellent qualitative agreement with the recent Voyager 1 observations corresponding to the 10 mbar level (Hanel *et al.*, 1979).

A second feature of their data, which was

[1] Visiting astronomer, Kitt Peak National Observatory, which is operated by the Association of Universities in Astronomy, Inc., under contract with the National Science Foundation.

[2] Now at University of Hawaii, Honolulu, Hawaii.

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not discussed by Caldwell *et al.* (1979), is the anticorrelation between the fine details of the 7.9-μm scan, superimposed upon the general north–south trend, and those of the 17.8-μm scan. This is evident in Fig. 1, where the two scans are reproduced, juxtaposed with a portion of the Mercator image of Jupiter obtained from the Voyager I spacecraft, as given by Smith *et al.* (1979, their Fig. 1). Figure 1 of the present paper further shows the relationship of visual features to the infrared. In particular, the North and South Tropical Zones, near latitudes $\pm 25°$, exhibit enhanced emission, relative to the surrounding latitudes, at 7.9 μm, and depressed relative emission at 17.8 μm. The enhanced 7.9-μm emission in the Tropical Zones, implying enhanced stratospheric temperature in the vicinity of the 10-mbar level, is also qualitatively consistent with the Voyager I observations (Hanel *et al.*, 1979, their Fig. 4).

Figure 1 also demonstrates that the troposphere, which is characterized both by the longer-wavelength infrared radiation and by the visual image, does not have a simple north–south symmetry. This suggests that the tropospheric thermal structure is not governed by seasonal effects. However, Fig. 1 does imply that whatever mechanisms dominate the troposphere also influence the stratosphere by imposing small systematic perturbations on the basic north–south trend in 7.9-μm emission.

In the present paper we give a possible explanation for the enhanced 7.9-μm emission corresponding to the North and South Tropical Zones (NTrZ and STrZ). We suggest that this is due to differential stratospheric heating by visible and near-infrared CH_4 bands, which is caused by higher clouds in the NTrZ and STrZ relative to the North and South Equatorial Belts (NEB and SEB). Solar radiation reflected from high clouds suffers less atmospheric absorption before returning upward to the stratosphere, so that it can heat the stratosphere more there than it can over latitudes where the clouds are lower.

In this regard, we note that belts and zones have different effective temperatures. Orton (1975) has derived effective temperatures of 127.6°K for the SEB and 124.2°K for the STrZ from Pioneer 10 radiometry. Our observations (Figs. 1 and 2 of Caldwell *et al.*, 1979) are qualitatively consistent with Orton's results. The lower emission from the STrZ, relative to the SEB, would imply a higher (and thus colder) cloud over the STrZ which, by preceding arguments, could result in a warmer overlying stratosphere, consistent with the anticorrelation of the 7.9- and 17.8-μm features in Fig. 1.

We further note that Orton and Ingersoll (1976), and Terrile *et al.* (1978), suggest that high ammonia clouds exist over the zones but not over the belts. An alternate interpretation is given by Sato and Hanson (1979), who conclude that there are ammonia clouds over both the zones and belts. But they further indicate that scattering layers in the range 150–500 mbar reach higher altitudes over the NTrZ than over the NEB. For present purposes it is not necessary to differentiate between these two possible scenarios.

Since the TrZ and EB regions on Jupiter define one of the anticorrelation features between 7.9 and 17.8 μm, we adopt a variable cloud height, or effective scattering level, between the TrZ and EB as a parameter in our study, and we choose an effective scattering level of 0.3 bar for the TrZ. This value would appear to be crudely consistent with the study by Sato and Hanson (1979). Although Orton's (1975) results refer to the opposite hemisphere, we are concerned here with an approximately symmetric effect north and south, and we also adopt Orton's effective temperatures for the TrZ and EB in this paper.

FORMULATION OF THE MODEL

We will use the basic procedure of Cess and Chen (1975) with modifications. We begin by altering their expression for stratospheric heating by CH_4 [Cess and Chen

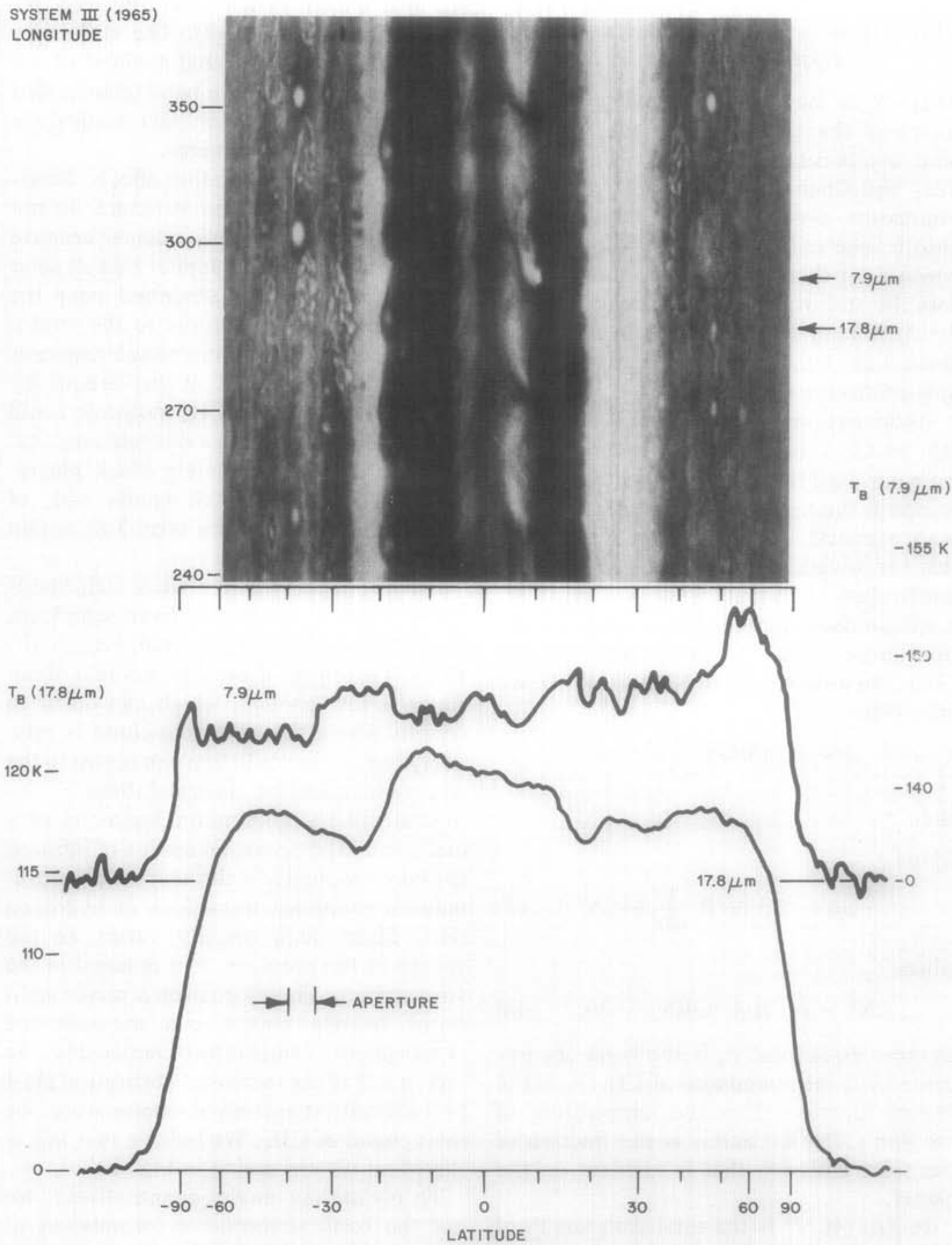

FIG. 1. Ground-based infrared scans along the central meridian of Jupiter from 8 March 1979 compared with Voyager I spacecraft imaging from February 1979. The visual image extends from latitude +90° to −60°. The system III (1965) longitudes corresponding to the infrared scans are shown by the two respective arrows.

(1975), their Eq. (5)] as follows:

$$(dF/dP)_{\text{bands}} = \Sigma K_j(\mu) + R_c \Sigma K_j^*(\mu) - \Sigma J_i, \quad (1)$$

where R_c is the cloud reflectivity, μ is the cosine of the solar zenith angle, and the other symbols have the same meaning as in Cess and Chen. The subscript j refers to summation over those CH_4 bands which absorb solar radiation, and i to those bands which emit thermal radiation and thereby cool the stratosphere. The second term on the right-hand side of Eq. (1) incorporates absorption by CH_4 of sunlight reflected upward from a cloud deck.

Ultimately, we will use the analog of Eq. (10) of Cess and Chen, however derived from our Eq. (1) rather than their Eq. (5), to compute the variation of temperature, T, with pressure, P. Here again we assume that the Jovian stratosphere is in radiative equilibrium, such that $dF/dP = 0$. But first, it will be necessary to evaluate the absorption terms in Eq. (1). Following Cess and Chen, and also Cess and Khetan (1973), we may write

$$K_j(\mu) = \mu\alpha e_{\omega_j}(T_s)(N/P) \frac{d}{dN}[A_j(N/\mu)] \quad (2)$$

and

$$K_j^*(\mu) = -\mu\alpha e_{\omega_j}(T_s)(N/P) \frac{d}{dN}[A_j(N^*)], \quad (3)$$

where

$$N^* = N_c/\mu + 1.8(N_c - N). \quad (4)$$

In these equations, A_j is the band absorptance; N is the abundance of CH_4; e_ω is the Planck function; T_s is the temperature of the Sun (5785°K); and α is the fraction of the solar emission that is incident on the planet.

In Eq. (4) N^* is the total path length of CH_4 sampled by solar radiation, first down to the cloud tops N_c/μ and then back to the altitude above where the abundance is N. In using this equation below, we will invoke the approximation $N_c \gg N$, which is certainly true in the stratosphere, to simplify Eq. (4), except when it is required for differentiation in Eq. (3). The diffusivity factor for upward reflected sunlight of 1.8 represents an average for band regimes that we encounter for Jupiter. Our results are insensitive to this parameter.

Because of line saturation effects, bands having conventional line structure do not contribute to ΣK_j^*. This occurs because there is enough CH_4 on Jupiter that all solar radiation in a line is absorbed near the cloud tops before it returns to the stratosphere. The extra pressure broadening near the clouds means that at any frequency where a stratospheric CH_4 molecule could absorb a solar photon in a discrete line, that molecule sees a completely black planet. Line absorption in such bands will, of course, contribute to the term ΣK_j within Eq. (1).

However, many of the weak CH_4 bands below about 1 μm do not have significant line structure (Lutz *et al.*, 1976; Fink *et al.*, 1977). Therefore, if the CH_4 column abundance is low enough, which can occur in regions where the reflecting cloud is relatively high, some radiation can return to the stratosphere and be absorbed there.

Stratospheric cooling on Jupiter is very inefficient. The dominant source of infrared emission on Jupiter is through the pressure-induced rotational transitions of hydrogen (H_2). Since such opacity varies as the square of the pressure, it is minimal in the stratosphere. Therefore even a minor additional heating source can increase the stratospheric temperature noticeably. In fact, much of the increased absorption must be radiated, at increased temperature, by the ν_4 band of CH_4. We believe that this is the effect we are seeing in Fig. 1.

To pursue our model quantitatively, we use the band absorptance formulation of Lutz *et al.* (1976) for the weaker bands below 1 μm, and a more recent extension (Lutz *et al.* in preparation) for the stronger bands. For the present application, their band absorptance results may be approximated by:

$$A(N) = (A_0/0.36)\{1 - \exp(-0.36\, SN/A_0)\}, \quad (5)$$

where S is the band intensity and A_0 is the bandwidth parameter.

At the equinox, which is close to the present Jovian season, $\mu = \cos\theta \cos \Omega t$, where θ is the latitude and Ω the planet's rotational velocity. With the notation $\tau = \Omega t$, the diurnally averaged value of K_j^* is

$$K_j^* = \int_{-\pi/2}^{\pi/2} K_j^*(\mu) d\tau. \quad (6)$$

Combining Eqs. (3), (4), (5), and (6) (with the approximation that $N_c \gg N$) yields

$$K_j^* = 1.8(\cos\theta)\alpha e_{\omega_j}(T_s)(SN/P)\exp(-0.648\, SN_c/A_0) E(SN_c/A_0 \cos\theta), \quad (7)$$

and

$$E(x) = (1/2\pi) \int_{-\pi/2}^{\pi/2} (\cos\tau)\exp(-0.36x/\cos\tau) d\tau. \quad (8)$$

To evaluate the individual K_j^*'s for summation in Eq. (1) according to Eq. (7), we used the parameters listed in Table I. The band strengths are from Giver (1978). The bandwidth parameters refer to a typical stratospheric temperature of 140°K and were obtained by square-root temperature scaling of room temperature values (Lutz *et al.*, 1976). The room temperature A_0 values for the 11,530 through 16,160-cm^{-1} bands were taken to be the same as the 13,760- and 16,160-cm^{-1} values of Lutz *et al.* (in preparation). For the 10,010- and 11,250-cm^{-1} bands, A_0 was evaluated from the absorption coefficient data of Fink *et al.* (1977), employing the same procedure as that of Lutz *et al.* (1976).

TABLE I

METHANE BAND PARAMETERS

Band center (cm^{-1})	S (cm^{-1}(km-am)$^{-1}$)	A_0 (cm^{-1})
10,010	6330	154
11,250	6380	154
11,530	871	102
11,890	119	102
12,660	469	102
13,760	825	102
16,160	143	102

We chose 20° as a latitude typical of the transition from EB to TrZ, and $R_c = 0.83$ (Wallace *et al.*, 1974). In particular, we did not choose different values of R_c for belt and zone. Finally, we used the effective belt and zone temperatures given by Orton (1975).

RESULTS AND DISCUSSION

Using the analog of Eq. (10) of Cess and Chen, as derived from our Eq. (1) together with the above procedure, and asusming a CH_4 to H_2 mixing ratio of 2×10^3 (Lutz *et al.*, 1976), we have plotted the difference in temperature between the TrZ and EB as a function of atmospheric pressure; this is shown in Fig. 2. As previously discussed, we have adopted an effective scattering pressure at the cloud tops of 0.3 bar for the TrZ, and we illustrate the resulting stratospheric temperature difference, T(Tr) − T(EB), for various assumed effective scattering pressures, P_2, of the EB cloud tops. We have not extended these results to altitudes below the 50-mbar level, since the radiation model for CH_4 bands with line structure which we have employed (Cess and Chen, 1975) becomes inapplicable at higher pressures.

Note that for $P_2 = 0.3$ bar, that is, if the TrZ and EB cloud tops are at the same altitude such that there is no differential solar heating by weak CH_4 bands, then the TrZ stratosphere would be everywhere colder than the EB. This follows from the different observed effective temperatures of the two regions on Jupiter which have been employed within the model, producing reduced absorption of upward infrared radiation by H_2 within the TrZ stratosphere as compared with the EB.

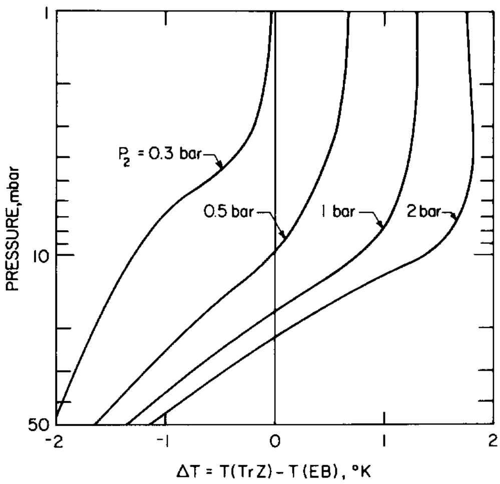

FIG. 2. Stratospheric temperature differentials due to differences in cloud-top altitudes. The pressure level of the cloud top over the zone is 0.3 bar. The values of P_2, the pressure level of the cloud top over the belt, parametrize the temperature difference shown here as a function of pressure in the Jovian stratosphere.

However, if the effective cloud top pressure for the EB is 1 or 2 bar, then the stratospheric temperature differential from TrZ to EB at 10 mbar is about +1.5°K, which is in fair agreement with the 7.9-μm scan in Fig. 1. Moreover, as previously discussed, a variation in cloud altitude between TrZ and EB is consistent with the observed differences in effective temperature.

In summary, then, our model with latitudinally variable cloud top altitude, and with different effective temperatures between TrZ and EB, is capable of explaining the anticorrelation between emission details in the stratosphere and in the troposphere. However, since the latitudinal variation in effective scattering level is poorly known, and since the ΔT results in Fig. 2 are highly sensitive to the choice of the effective scattering level, our model results can only be regarded as suggestive. For example, if the effective scattering pressure were taken to be 0.2 bar, instead of 0.3 bar, then ΔT at the 1-mbar level would be twice that shown in Fig. 2.

While we feel that our explanation is sound concerning depressed tropospheric emission in the TrZ being due to high clouds, we do not discount other possible mechanisms for enhanced stratospheric temperatures in the TrZ. An important source of Jovian stratospheric heating is through solar absorption by some unknown aerosol, and from our extension of the Cess–Chen (1975) model we have assumed the concentration of this aerosol to be independent of latitude. But Hord *et al.* (1979) have demonstrated possible latitudinal variability in aerosol concentration for Jupiter employing the Voyager II photopolarimeter. Moreover, our model does not incorporate possible dynamical influences.

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